

MECHANICAL BEHAVIOR OF CONSTRUCTION MATERIALS: RATE AND TEMPERATURE
PHENOMENA

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Research Report:

1.0 Numerical Modeling of Ice-Structure Interaction

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The objective of this research is to investigate using numerical models the mechanics of deformation and progressive failure in ice for the purpose of predicting global forces and local pressures generated on offshore structures proposed for deployment in the Arctic. Three major areas of study are involved: (a) the development of generalized constitutive theories for characterizing deformation by flow, distributed cracking, and localized crack propagation in ice; (b) the development of finite element methods of analysis to account for nonlinearly viscoelastic flow and smeared crack models of ice; and (c) the numerical simulation of ice-structure interaction processes for ice sheets indenting rigid cylindrical structures.

1.1 Multiaxial Differential Flow Law for Polycrystalline Ice: In ice-structure interaction problems where only "steady state" flow is of interest, an elastic - power law model of deformation in ice (sometimes without the elastic component) is adequate. The multiaxial generalization follows from conventional elasticity theory and from the rate theory of flow. The multiaxial law for incompressible flow of isotropic ice has been presented by A.C. Palmer. However, in general, polycrystalline ice is an anisotropic material because of its hexagonal crystal structure and preferred grain orientation during solidification. An orthotropic model of incompressible flow has been developed to describe texture anisotropy in ice and equations have been derived for estimating the model parameters from uniaxial test data.

However, both the elastic and "transient" flow behavior of ice are of great importance in a broad range of ice mechanics problems. A multiaxial differential flow law has been developed to model the elastic, transient, and steady flow in polycrystalline ice. Flow (or creep) is modeled in terms of two nonlinear deformation-rate mechanisms: the first mechanism governs the transient deformation-rate (creep) which decays to zero as an elastic back stress measure increases asymptotically; the second mechanism, which is modeled in terms of the well-known power law, governs the viscous deformation-rate. The transient deformation, an internal state variable, defines the magnitude and direction of

prior deformation history in the material. The uniaxial model satisfies the dimensional requirements identified by M.F. Ashby and P. Duval. Closed form analytical solutions are derived for constant stress creep loading and recovery.

The multiaxial generalization follows from conventional elasticity theory and from the rate theory of flow for the viscous and transient deformation-rates. The rate theory assumes normality of the viscous deformation-rate to a scalar valued flow potential expressed in terms of an equivalent stress measure for orthotropic and incompressible materials. In addition, the model obeys the constraint conditions required to ensure compatibility of strains and equilibrium of stresses in the spring-dashpot network representation. History effects are modeled with a kinematically hardening multiaxial formulation based on the transient strain (or, equivalently, the elastic back stress) vector.

The uniaxial model contains a total of five parameters that can be determined from conventional experimental testing methods. The model has been verified against the comprehensive creep data of T.H. Jacka as well as the data of N.K. Sinha. Predictions of the ratio of transient strain to total strain agree with those of Sinha's (contained in his seminal 1979 paper in the Philosophical Magazine A.) In consistency with the incompressible flow of glacier ice, the model predicts pressure-insensitive behavior under conventional triaxial loading conditions. Also, theoretical predictions agree with Frederking's (1977) data from constant strain rate tests carried out under plane strain conditions (although it should be noted that his data is for ice with loading induced damage/distributed cracking, not pure flow.)

1.2 Rate-Sensitive Failure Criterion for Ice: At low rates of loading, ice is a purely "ductile" material and its behavior can be characterized with flow theory. However, as the rate of loading is increased cracks can form in ice. Under tensile loading, the first crack which forms propagates in an unstable manner in ice with large grain sizes and at moderate to high rates of loading. These conditions are representative of most engineering applications. Consequently, the stress at which the first crack forms defines the tensile strength of ice. On the other hand, the first crack which forms under compressive loading is stable and has been linked to the yield point phenomenon in ice. The material can sustain additional compressive stress prior to reaching its ultimate strength.

The link between first crack formation under tensile and compressive states of loading has been investigated. This is based on the limiting tensile strain, i.e., the strain at which a tensile specimen fails at a given rate of loading. It has been shown that under compressive loading the first crack forms when the lateral tensile strain resulting from the Poisson effect and incompressibility condition of flow equals the limiting tensile strain. The predicted time to formation of the first crack in ice under compressive using loading agrees well with the experimental data of L.W. Gold. Consequently, it has been possible to establish a definite relationship between tensile strength and yield in compression. In particular, for an elastic material the ratio of the tensile strength to the yield stress in compression must equal the Poisson's ratio. This prediction is supported by experimental evidence on ice under tension-compression states of stress. Using the more general relationship to account for flow in ice, a rate sensitive yield/failure surface has been developed using the Drucker-Prager formulation.

1.3 Fracture Characterization of Ice: Knowledge of tensile strength is

important, but by no means sufficient to characterize the tensile fracture of ice. A toughness or energy measure is necessary to quantify the stress at which a pre-existing crack will propagate. Linear elastic fracture mechanics has been applied by several investigators for determining the fracture toughness of ice. The general testing methodology, particularly the selection of specimen sizes, has been borrowed from metal plasticity. However, ice is very different from metals. Metals are highly ductile and the plastic zone surrounding the crack tip absorbs most of the energy, which can be more than 1000 times the energy required for creating the new surfaces as the crack advances. On the other hand, ice displays both "quasi-brittle" and "creep" behavior depending on the temperature and rate of loading. In ideally brittle materials, e.g., glass, almost all the energy is consumed in creating the new surfaces with negligible energy dissipation in the "process" zone ahead of the crack tip. The stresses near the crack tip can approach the theoretical tensile strength of the material.

The objectives of the research are to (a) establish the conditions under which linear elastic fracture mechanics is applicable and that under which a nonlinear characterization of fracture behavior is necessary; and (b) characterize the fracture toughness of ice when linear elastic fracture mechanics theory is not applicable. The initial effort has been concerned with understanding the toughening mechanisms at high rates of loading and low temperatures where ice behaves as a "quasi-brittle" material. In such materials, the process zone is localized on a plane and does not resemble the kidney shaped plastic zone of metals. The process zone behavior is characterized in terms of a stress-separation relationship. Predictions of the process zone size and critical crack tip opening displacement have been made. The latter predictions agree with the limited experimental evidence currently available for ice. It has been shown that process zone size estimates based on the stress-separation model are significantly greater than those from the formulation used in metal plasticity or for materials obeying a power law of creep. Using the stress-separation model in conjunction with the tensile flow law and strength model, an objective energy release rate criterion has been developed for numerically simulating tensile cracking in ice based on the blunt crack band theory.

1.4 Sea Ice Indentation in the Creeping Mode: A finite element method of analysis has been developed for the nonlinear viscoelastic behavior of ice based on a weighted equilibrium-rate formulation. The rate formulation allows realistic simulation of the spatial-temporal variability in the strain rate field and no empirical definition of an average strain rate measure is necessary as in ice load models derived from plasticity theory. The kinematically hardening constitutive model of flow consists of stiff differential equations that pose serious stability and efficiency limitations. An efficient explicit-implicit numerical integration algorithm based on a gradient (Newton-Raphson) technique has been developed which enables fast convergence in problems where inelastic deformations dominate. Variable interface conditions between the ice feature and the structure can be simulated to bound the effects of interface bond or friction. In particular, a "free" interface condition, which represents no adfreeze or friction, is simulated by an adaptive procedure that allows only normal compressive stresses to develop at the interface.

Numerical simulation studies have been performed under plane stress conditions to study the sea ice indentation problem for wide structures under steady flow conditions. Creep is the predominant mode of deformation for artificial islands in the Arctic nearshore region during "breakout" and/or steady

indentation conditions occurring during winter. Further, stresses, strains and strain rates resulting from creep are necessary to predict the growth and propagation of localized and distributed cracks when rate effects influence fracture behavior. The numerical simulations quantify the effect of (i) material model, i.e., isotropic versus transversely isotropic; (ii) natural variability in material parameters; (iii) approximate versus "exact" methods of analysis and the ability of each to model interface adfreeze and friction as well as spatial-temporal variability in the strain rate field; and (iv) grounded rubble pile or accreted ice foot. Theoretical predictions of pressure-area curves used in the design of structural components have been developed.

2.0 Low Temperature Materials and Structural Models Testing Facility

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The Low Temperature Materials and Structural Models Testing Facility, under development at MIT, will allow experimental research at temperatures in the range of -50°C to 0°C . The facility will include the special sample preparation and testing equipment as well as data acquisition system listed below:

- (1) Three cold rooms: for (i) growing seed ice crystals and ice specimens; (ii) sample preparation, thin section photography, and post test sample preparation of SEM analysis; and (iii) mechanical testing. The testing room will be capable of temperature control to within 0.2°C or better. Temperature in the growth room may be reduced up to -10°C with the same variation, but this room will also be able to sustain a temperature gradient in the vertical direction. The third room will operate at temperatures between 0° and -2°C with a coarse temperature control.
- (2) Loading frame rated at 220 kips and cross-head speed of 1 in/s and able to accommodate variable size specimens up to 30 in: the frame will be a general purpose four-post uniaxial system capable of applying compression, tension and cyclic loading. Independent control of the radial stress for triaxial testing will be accomplished using a servo-controlled valve attached to a transfer barrier. The hydraulic actuator will be rated at 360 kips in order to deliver 220 kips at 1 in/s. The design will minimize mechanical noise for acoustic emission monitoring.
- (3) Triaxial cell to accommodate specimen sizes up to 6 inches in diameter and 14 inches in height. The device will include an internal load cell as well as radial and axial deformation transducers. This cell will be capable of delivering a confining pressure of up to 12 ksi.
- (4) Acoustic emission monitoring system with host computer, transducers and multi-channel monitoring system. Available software for location analysis will be included, while others will be written.
- (5) Data acquisition system composed of a microprocessor/controller and a high speed analog to digital converter. The systems will include (i)

multi-channel signal conditioning, (ii) high speed multiplexer and voltmeter, (iii) computer based controller, and (iv) data processing and graphics display.

3.0 Mechanics of Damage in Construction Materials

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Sponsorship: Army Research Office

Rate mechanisms govern the mechanical behavior of construction materials under three conditions: (1) at high homologous temperatures; (2) when subjected to short-term loading that is quasi-static, impulsive, or vibratory; and (3) when subjected to sustained (or creep) loading over long times. Examples of advanced construction materials satisfying one or more of these conditions include:

- (a) Polymer matrix structural composites such as FRPs.
- (b) Single-ply roofing membranes made of elastomers.
- (c) Polycrystalline ice in cold regions engineering.
- (d) Cementitious composites such as high-strength concretes and FRCs.

The deformation and progressive failure of such rate sensitive materials are strongly influenced by three mechanisms: flow, distributed cracking, and localized crack propagation. The interaction of these mechanisms and their characterization is a problem of considerable research interest.

Any given material may display purely ductile, purely brittle or combined behavior depending upon the temperature and conditions of loading. The mechanism of flow and the constitutive framework of rate theory is sufficient for characterizing purely ductile behavior associated with dislocation movements or diffusion processes. On the other hand, the mechanism of distributed cracking and the constitutive framework of damage theory is sufficient for characterizing the ductile-to-brittle transition or purely brittle behavior associated with the formation and stable growth of cracks and/or voids. Consequently, damage controls the process of failure in engineering materials prior to localization of fracture (formation and propagation of a single crack.) The ultimate strength and post-peak response of such materials is generally governed by damage. This phenomenon is particularly significant when the state of stress involves compression.

The objective of this research is to understand and characterize damage processes and the interaction mechanisms between damage and flow in advanced construction materials. In particular, this study is investigating the influence of confining pressure on damage during constant strain rate loading and under conventional triaxial states of stress. At low rates of loading materials tend to display purely ductile behavior. As the rate of loading is increased, stable cracks may form under compressive loading. As the deformation increases, the extent of this distributed cracking phenomenon may increase causing the material to fail by "crushing." The distributed cracking phenomenon weakens the material; under constant strain rate loading this contributes to "strain-softening" and under constant stress loading to "tertiary" creep. The application of a low to moderate level of confining pressure tends to suppress the formation and growth of stable cracks, which in turn allows a higher shear/distortional stress to be sustained. As the confining pressure is further increased the material displays pressure insensitive ductile flow, and eventually at very high confining pressures

the material may undergo a change in morphology or phase.

The following specific tasks are being undertaken: (1) To generate a comprehensive set of experimental under uniaxial and cylindrical triaxial loading at constant strain rates for characterizing the deformation of materials when damage processes are active; (2) To investigate the formation of "first" cracks during deformation under both uniaxial and triaxial loading by monitoring acoustic emissions; (3) To develop and apply quantitative acoustic emission theory for locating cracks (position, time, direction, and size) under uniaxial and triaxial loading conditions; and (4) To theoretically characterize the rate-sensitive evolution of damage during deformation by flow. Three classes of materials are under consideration: homogeneous and isotropic; homogeneous, but anisotropic; non-homogeneous, but isotropic (e.g., random short-fiber reinforced composites.)

4.0 Control of Ice-Pavement Bond on Highways and Bridges

Personnel: S. Shyam-Sunder, N. Sonwalkar

Sponsorship: NSF

The objective of this research is to conduct fundamental studies on the formation of ice-pavement bond and the influence of temperature on bond strength. This involves a study of the intramolecular and intermolecular bond structure and its correlation with the mechanical behavior of the bond. The bond structure and formation is being determined with laser-based Raman microprobe spectroscopy. The long term goal of the research is to help reduce the reliance on environmentally and mechanically undesirable deicing chemicals such as salt.

According to the microscopic theory of adhesion, wetting of the substrate surface and subsequent sintering of the ice crystals is the primary cause for the development of the adhesive bond between ice and the solid substrate. Wetting creates a molecular interfacial contact between ice and the substrate, while the subsequent sintering between ice crystals which imparts motion to the crystals leads to a configuration with absorptive equilibrium. In the process, molecules diffuse across the interfacial zone. As a consequence, the molecular forces and conformational energy at the interface is different from that of the bulk. Temperature is a major parameter governing the interface bond strength.

For the first time, micro-Raman fast scan ($1200 \text{ cm}^{-1}/\text{s}$) spectroscopy has been used to observe the phase transition of water to ice and to obtain information on the crystallinity of the thin interface ice-layer formed by vapor deposition on a copper substrate. The results are in excellent agreement with those from single channel slow scanning equipment and, therefore, establishes the feasibility of a powerful analytical tool for time and space resolved spectroscopic measurements of the interface. Preliminary data seems to indicate an amorphous interface between ice and copper; confirming the anticipated difference in interface structure.

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